CLIMATIC CONTROL OF SOIL ACIDITY

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Abstract: A curve-fit model of the relationship between soil pH (A horizon) and climate forms the basis of a map of predicted pH for the conterminous United States. This map was produced with the aid of a large climatic data base, a computer mapping program and subroutines to map modeled values of soil pH. Patterns of pH follow well-recognized patterns of climate, although the pH of 7 line deviates greatly from Marbut's line dividing pedalfers from pedocals. The overall accuracy of the map and model was checked using a validation data set. Geographic patterns of pH are realistic, although land use, topography, and parent material may cause local variations about the predicted mean for a given region. Several apparently anamolous map patterns were also checked but found to be accurate. Prediction of the detailed pattern of pH will require variables in addition to climate.

INTRODUCTION

Soil pH has long been recognized as an important soil property, as evidenced by the voluminous literature related to its study. The few geographical studies of soil pH that have been conducted ranged in scale from extreme local scale to large regions (Jenny and Leonard, 1934; Jenny, 1941; Rode, 1962; Richmond, 1962; Gerasimov and Glazovskaya, 1965; Westin, 1976). In most of these studies, the change in soil pH values with the spatial gradients of climate has been recognized. Yet few of these studies have clearly defined the quantitative spatial relationships between climate and soil acidity. Existing climate-soil pH models are often limited by special data requirements and various assumptions that restrict their application over large areas.

The primary purpose of this study is to determine the relationship between climatic variables, especially the water balance variables with A horizon soil pH at the scale of the entire United States. Secondly, we wish to determine the strength of these relationships and develop a general climatic and geographic model suitable for predicting soil pH. Thirdly, we wish to map predicted A horizon soil pH for the United States based upon the soil pH-climate relationship.

The relationship between soil-forming processes and climate was first established by Dokuchaev in the 19th century (Joffe, 1936). Marbut applied much of the early soil science research to soils in the United States and derived a soil classification scheme based on acid (pedalfer) and alkali (pedocal) soils. He too found climate, particularly precipitation, to be an important determinant in the development of these soil types (Jenny, 1941). Jenny and Leonard (1934) sampled soils on a transect across the great plains and plotted the change in pH and exchangeable hydrogen ions with rainfall. Kohnke, Stuff, and Miller (1968) related soil pH with vegetation type and a climatic index termed the *biofactor*, which consists of the ratio of annual precipitation over Holdridge's *biotemperature*. They formed a multiple linear regression with pH as the dependent variable and *biofactor* and *cation exchange capacity* as the independent variables. They used data "from many countries of the world," but the multiple R value was only 0.65. Westin (1976), working in North Dakota, also reported a strong relationship between temperature and precipitation and soil pH.

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As with some other researchers, however, he believed that parent material plays a large role in determining soil acidity levels. Westin's work was based on non-parametric statistics, making it difficult to assess the relative influences of climate and parent material on soil pH balance. Much additional geographic research on soil acidity has been undertaken, but these workers were much more concerned with describing and measuring the spatial variation of soil pH than with developing physically-based predictive models of pH (Campbell, 1978).

Soil pH is measured as the negative logarithm of hydrogen ion activity in the soil (Buol, Hole, and McCraken, 1973). The flux of soil moisture into and out of the soil profile determines the availability of soil H^+ ions, the rate of accumulation and removal of soil bases from the profile, and the degree of interaction between the H^+ ions with soil cations. The equilibrium established between these elements of the soil water system determines the H^+ ion activity level or soil pH. It is not surprising, therefore, that many authors have found a relationship between some index of environmental moisture and pH.

DATA COLLECTION

Soil pH data were collected from *Soil Survey Investigations Reports* compiled by the Soil Conservation Service (USDA, various dates). These reports cover most of the conterminous 48 states as well as Hawaii, Puerto Rico, and the U.S. territories, and contain detailed data on soil chemical and morphological characteristics for thousands of soil profiles. For all of the profiles selected for this study, slope, topographic position, and vegetation type were also reported.

From these reports, a stratified random sample of investigated profiles was selected. An attempt was made to select sample sites from as large a span of climatic environments as possible, including several tropical sites from Puerto Rico. From this data set, only freely-drained, mature soils were retained for analysis so that local conditions, such as poor drainage due to topographic position or high water tables, would not obscure the effect of climate. Furthermore, soil pH values (based on the 1:1 soil water ratio method) for the A horizon were used because pH values from other horizons are not always measured and reported and because the A horizon is in more intimate contact with climatic forces. The final data set contained 45 sites.

For each sample site, soil chemical and morphological properties, vegetation type and climatic variables were determined. The soil property variables and vegetation type were obtained from the *Soil Survey Investigations Reports* (Table 1). The climatic variables were obtained by reconstructing the climatic environment at each site from nearby weather stations which report both temperature and precipitation (U.S. Dept. of Commerce–N.O.A.A.). Average annual and monthly temperature and precipitation were reconstructed as well as measures of seasonality at each site (Table 1).

An average monthly water balance was calculated from the weather data at each site using Thornthwaite's modulated water budget (Thornthwaite and Mather, 1957). For some sites, the water budget variables were available in *Average Climatic Water Balance Data for the Continents: Part VII United States* (C. W. Thornthwaite Associates, 1964). The water balance variables were chosen for use in this analysis because they are superior indicators of the soil moisture environment. Soil moisture

Table 1. List of Independent Variables Selected for Development of a Soil pH Model

Climatic variables (average annual values)[1]		Soil property variables[2]
1. Potential evapotranspiration (PET)	10. Temperature of coldest month	1. Total organic carbon
2. Actual evapotranspiration (AET)	11. Temperature range	2. Carbon A horizon
3. Actual/potential evapotranspiration	12. Precipitation minimum month	3. Soil profile depth
4. Arkley's leaching index	13. Precipitation maximum month	4. Total carbon/depth
5. Deficit minus surplus	14. Summer precipitation	5. Carbon/nitrogen
6. Index of moisture		6. Vegetation
7. Temperature		
8. Precipitation		
9. Temperature of warmest month		

Sources: [1]C. W. Thornthwaite Associates (1964); National Oceanic and Atmospheric Administration; calculated by authors.
[2]U.S.D.A.

is known to control soil pH dynamics. In addition, the water balance variables can be used to calculate various indices of the soil environment which have been used by other workers (Table 1).

METHODOLOGY AND RESULTS

Stepwise Multiple Regression and Correlation Analyses were performed using soil pH as the dependent variable and all the independent variables (Table 1). The total R was 0.96 and R^2 was 0.91, significant at the .001 level. The remaining 9% unexplained variation is probably caused by factors such as parent material, local topography, and measurement error; however, not all of the independent variables used in the multiple regression contributed equally to the explained variation. The first 3 variables entered into the regression equation accounted for 86% of the 91% total explained variation.

The best 3 variable model consists of the variables, soil moisture deficit minus surplus (DS), vegetation type (V) expressed as forests = 1 and other vegetation as = 0), and Thornthwaite's estimate of actual evapotranspiration (AET) (Table 2). The first

Table 2. Best Regression Models for Predicting pH Resulting from Stepwise Multiple Regression Using Independent Variables Shown in Table 1.

Step	Equation	R^2	SE
1	pH = 3.34 + 0.0028 (DS)	0.79	0.51
2	pH = 3.80 + 0.0025 (DS) - 0.63 (V)	0.83	0.45
3	pH = 5.01 + 0.0019 (DS) - 0.65 (V) - 0.0011 (AET)	0.86	0.41

All regressions are significant at the 0.001 level.

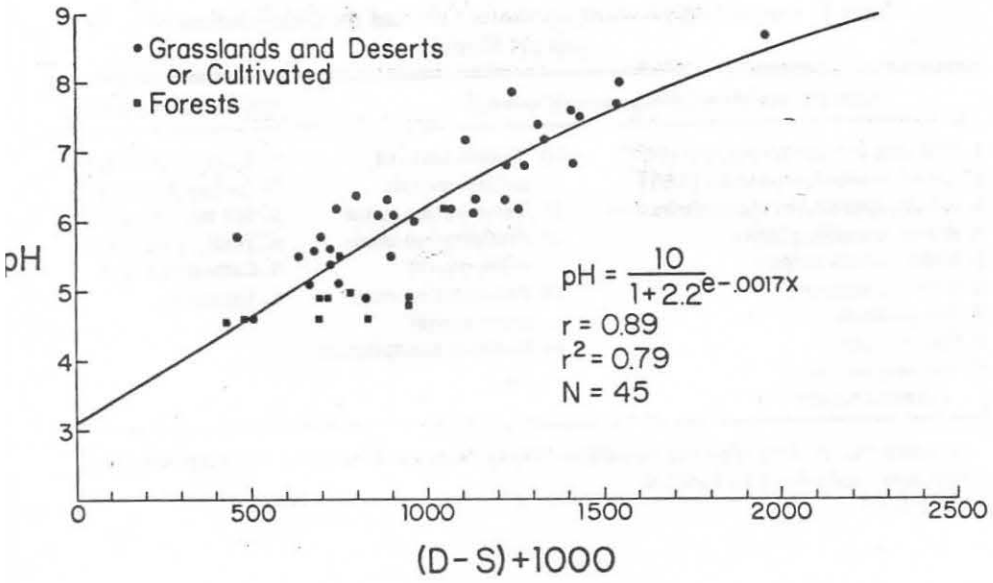

Fig. 1.

2 variables to enter, DS and V, form almost as good a predictive model with an R^2 of .83. An even simpler model can be formed from the regression of soil pH against the first variable to enter the regression equation, the soil water index (DS), which yielded an R^2 = .79. This suggests that a soil pH model, based on this single soil moisture index, would be an elegant predicator of soil pH.

Soil water index (DS) is a combination of 2 Thornthwaite water budget variables, average soil water deficit (D), and average soil water surplus (S). Neither variable alone is highly correlated with soil pH; however, the combination of the 2 variables, as D minus S, provides an index of the upward and downward forces of moisture representing the balance of forces supplying H^+ ions. In environments, where DS values are high, i.e., the generally more arid environments, an accumulation of soil cations occurs and hence soil pH levels are numerically high. In environments where DS values are low, much soil water is available and the leaching of soil bases is taking place during at least some portion of the year. This removal of soil bases lowers the soil pH level.

An examination of the soil pH with the soil water index regression revealed that in climates with extreme DS values unrealistic predictions of soil pH are possible because of the linear relationship. It is commonly reported that the pH of mineral soil varies worldwide from 3.5 to 10 (Brady, 1974). This suggested that the relationship is in reality curvilinear and probably in the form of a sigmoid curve where both upper and lower limits of soil pH can be defined. Jenny (1941) early on theorized that many of the relationships between climate and soil properties should be of the sigmoid form. Consequently, a sigmoid curve was fitted to the DS and soil pH data using a computer program (SPSS) based on the least squares method. An upper limit or asymptote of 10 was specified, in accordance with empirical findings; however, the r value and lower

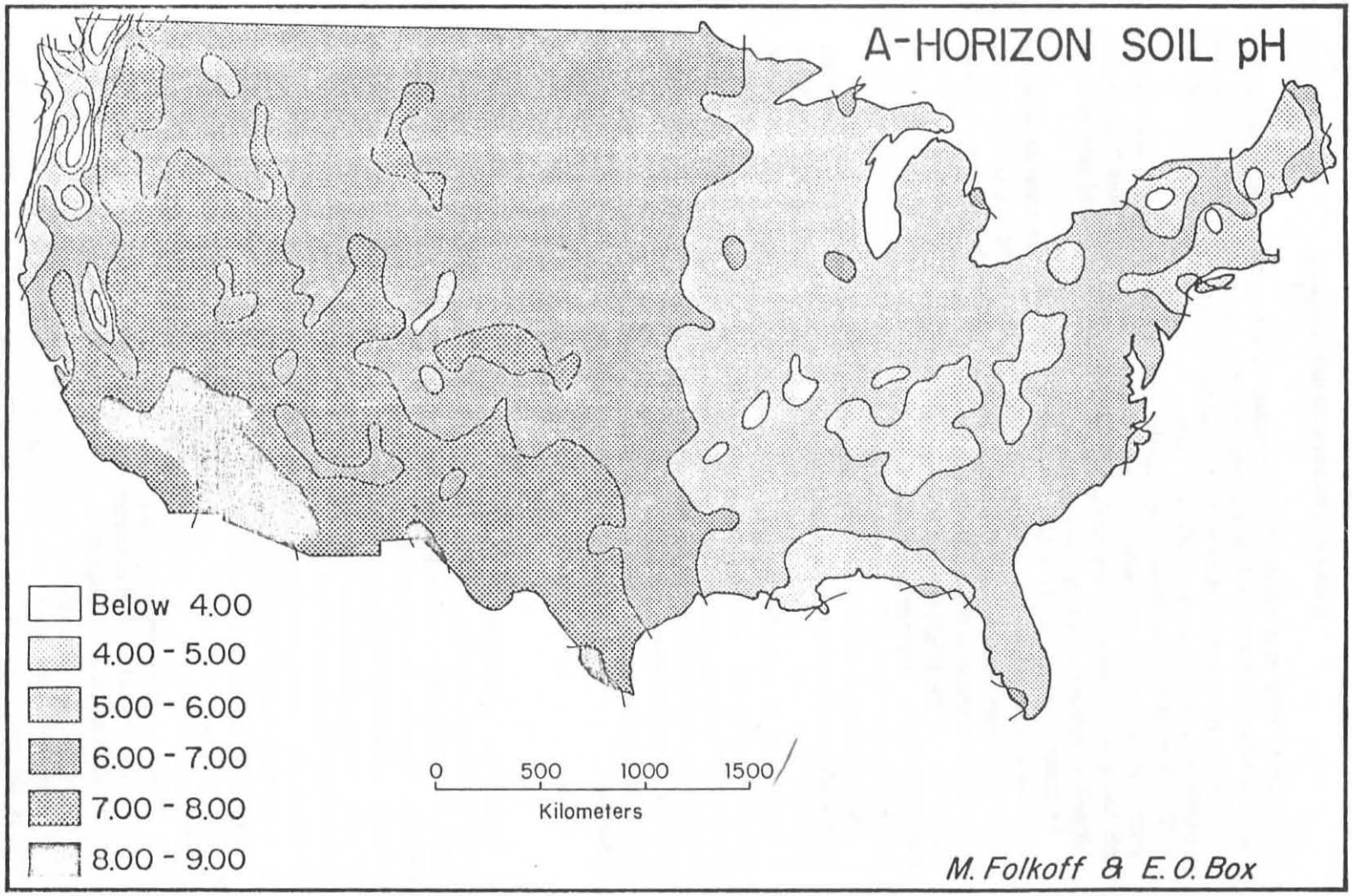
A-HORIZON SOIL pH
Below 4.00
4.00 - 5.00
5.00 - 6.00
6.00 - 7.00
7.00 - 8.00
8.00 - 9.00
0
500
1000
1500
Kilometers
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Fig. 2.

intercept or limit was calculated and selected by the computer program. To fit a sigmoid curve to these data, it was necessary also to add a constant of 1000 to each value of the soil water index to insure that all DS values had a positive sign. This new variable, labeled DS 1, is simply (D-S) + 1000.

The sigmoid transformation only slightly improved the r^2 to 0.79 and the program selected 3.13 as the lower limit of pH. This is reasonably close to the lowest pH levels found anywhere on earth. Figure 1 presents the central portion of the curve-fit as well as the new regression equation.

In order to map the pH values predicted by the regression equation presented in Figure 1, a large data base of annual soil moisture deficit and surplus was needed. These data were obtained for 1,182 U.S. climatic stations in computer adaptable form. Using methods developed by Box (1978, 1979), the mapping of predicted pH was performed by programming the regression equation in a SYMAP-based system and accessing the computer stored data base. This program simultaneously generated predictions of pH for 1,182 sites and mapped the results.

Figure 2 presents the resulting map. Because of the large number of stations used, the resolution of the map is quite good; however, the curve-fit equation smooths the detailed place-to-place variations in pH so that the general patterns of pH across the U.S. are easily recognized. We prefer this approach to mapping soil and ecosystem properties rather than techniques such as trend-surface analysis because it is highly flexible and produces, depending on climatic station density, more detailed patterns. In this case, the lowest pH values occur as expected in the humid northeast and portions of the northwest. Arid areas show high pH values. This pattern is based on climate alone; however, the key point is that now pH has been *quantitatively* tied to climate.

DISCUSSION

Initially 20 independent variables were chosen as potential predictor variables of A horizon pH, including climate, vegetation and soil morphochemical properties (Table 1). At the scale of the entire conterminous U.S., the climatic variables proved superior, especially the composite variable deficit minus surplus. Most of the accounted variance was supplied by climate in each of the best 3 and best 2 variable regression models. Vegetation type was also important, but this variable had to be dichotomized into presence and absence of forests (1 and 0's) and only 11 of the 45 soil profiles randomly selected were forested (Fig. 1). This uneven split makes the vegetation variable statistically inferior for a regression model. The forested sites generally do have a lower pH than nearby cultivated or grassland areas, as was demonstrated also by Keller and Frederickson (1952).

One variable (deficit minus surplus) was selected for further refinement as a predictor variable to form the basis of a computer generated map of pH (Fig. 2). Although it is recognized that pH is controlled by climate, it is also clear that temperature and precipitation are inferior to the water balance variables as indicators of the climate which actually enters the soil chemistry system and regulates H^+ ion balance.

The geographic patterns of pH presented in Figure 2 clearly follow climatic gradients. Of special interest, however, is the pH 7 isoline which occurs where DS = 1288. This line generally passes diagonally through the U.S. from the Gulf Coast of

Texas into eastern Washington. It is much different than the pedocal-pedalfer line drawn by Marbut, which parallels the 100th meridian. Actually the pH 6 isoline, which occurs where DS is 948, corresponds well with Marbut's line. In the arid southwest pH values exceed 8, but in no case are predicted values over 9.

The map also displays some unexpected patterns. These include areas in Kentucky and Tennessee, a region along the Gulf Coast from the Florida panhandle to Louisiana, an area in eastern North Carolina and eastern Michigan. Climatic data used for mapping in all these areas were checked for errors but none were found. The predicted values of pH in these seemingly anomalous areas must therefore be caused by climate alone. Consequently, a validation was performed by returning to the *Soil Survey Investigations Reports* for pH data in these and other areas.

A validation data set was selected for 15 soil profiles distributed throughout the U.S., including some sites in regions with apparently anomalous pH values (Table 3). For each site soil, pH values were estimated based on climate and the soil pH model for comparison with the actual A horizon pH at that site. To determine the validity of the model and map, the actual pH values were regressed against the predicted values, resulting in an $r = .81$. The high r value and level of significance (.01) indicate that the model is realistic.

There were, however, a few sites with large differences between actual and predicted pH values (Table 3). This may be caused by factors other than climate. In east-central Michigan, the predicted value (pH 5.9, site No. 7) was considerably lower than actual soil pH of 7.4. Although the map shows soil pH values for this region which are higher than the surrounding areas, the difference (1.5 pH) at this site is probably enhanced because it has recently been cultivated and has probably been fertilized and limed. A validation site in nearby central Michigan (site No. 6) does

Table 3. Data Set Used to Validate Sigmoid Model of Soil pH (Fig. 1) and Map of Estimated pH (Fig. 2)

Site	Actual pH[a]	Predicted pH[b]
1. MN	5.9	5.9
2. NH	4.8	5.0
3. VA	6.1	5.6
4. KT	6.0	5.0
5. TN	5.4	4.8
6. MI	6.0	5.7
7. MI	7.4	5.9
8. TX	5.5	5.4
9. NB	6.2	6.5
10. AZ	9.0	8.6
11. NV	6.7	7.3
12. PR	5.1	4.1
13. PR	5.6	4.8
14. HW	5.6	5.8
15. CA	6.6	7.3

[a] Based on U.S.D.A., *Soil Survey Investigations Reports*.
[b] Based on model presented in Figure 1.

not show this large a discrepancy, thus supporting the map as well as demonstrating the effects of factors other than climate.

The map, furthermore, shows that a region centered on western Kentucky and Tennessee has a predicted pH between 4 and 5. The actual values for validation sites falling in this area were somewhat higher than predicted. This is an area dominated by carbonate parent material which apparently alters the acidity values expected on the basis of climate alone. Informally, a few additional sites not shown in Table 3 were examined for this region and were found to be highly variable depending on land use. Nevertheless, the mean of the actual values is very close to the mean pH values predicted by the climatic model for this region.

The relationship between climate and soil pH is often believed to be obvious—the wetter the environment, the lower the soil pH. The curve-fit models developed here support this contention; however, we also see that pH, which chemically is in balance with the soil environment, correlates highest with the balance between soil moisture surplus and soil moisture deficits. Furthermore, pH has an upper and lower limit worldwide which supports the use of the sigmoid transformation used here.

The computer generated map presented is probably a reasonable geographic prediction, although many additional controls of pH could not at present be included. It is probably safe to say that the model and map are biased toward cultivated land, improved pasture and grasslands. Forests should have a pH about 0.5 lower than that mapped. Also, mountainous areas for which no climatic stations were available will not be accurately depicted on the map. And for some areas, the model seems to respond to urban heat island effects, as in the area mapped around New York City. These and other detailed patterns will require additional investigation.

BIBLIOGRAPHY

Box, E. O. (1978) Geographical dimensions of terrestrial net and gross primary production. *Radiation and Envl. Biophysics*, Vol. 15, 305-322.

Box, E. O. (1979) *Quantitative Cartographic Analysis: A Summary (with Geoenvironmental Applications) of SYMAP Auxiliary Programs Developed at the Jülich Nuclear Research Center.* Jülich (Germany): Kernforsehungsanlage Julich GmbH, Report No. 1582, 162 pp.

Brady, N. C. (1974) *The Nature and Properties of Soils* (8th ed.). Ames: Iowa State University Press.

Buol, S. W., Hole, F. D. and McCracken, R. J. (1973) *Soil Genesis and Classification.* Ames: Iowa State University Press.

C. W. Thornthwaite Associates (1964) Average climatic water balance data of the continents Part IV, United States. *Publications in Climatology*, Vol. 17 (3), 419-615.

Campbell, J. B. (1978) Spatial variation of sand content and pH within single contiguous delineations of two soil mapping units. *Soil Sci. Soc. Am. J.*, Vol. 42, 460–464.

Gerasimov, I. P. and Glazovskaya, M. A. (1965) *Fundamentals of Soil Science and Soil Geography.* Washington, D.C.: National Science Foundation. [Trans. by Israel Program for Scientific Translations, Jerusalem.]

Jenny, H. (1941) *Factors of Soil Formation.* New York: McGraw-Hill.

Jenny, H. and Leonard, C. D. (1934) Functional relationships between soil properties and rainfall. *Soil Science*, Vol. 38, 363-381.

Joffe, J. S. (1936) *Pedology.* New Brunswick: Rutgers University Press.

Keller, W. D. and Frederickson, A. F. (1952) Role of plants and colloidal acids in the mechanism of weathering. *American Journal of Science*, Vol. 250, 594-608.

Kohnke, H., Stuff, R. G., and Miller, P. A. (1968) Quantitative relations between climate and soil formation. *Zeit. fur Pflernahr Bodenk*, Vol. 119, 24-33.

Richmond, G. M. (1962) *Quaternary Stratigraphy of the La Sal Mountains, Utah.* U.S. Geol. Surv. Prof. Paper 324, 135 pp.

Rode, A. A. (1962) *Soil Science.* Washington, D.C.: National Science Foundation. [Trans. by Israel Program for Scientific Translations, Jerusalem.]

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service. *Climates of the States* (various dates).

U.S. Department of Agriculture, Soil Conservation Service. *Soil Survey Investigations Reports* (published by state and report number, various dates).

Thornthwaite, C. W. and Mather, J. R. (1957) Instructions and tables for computing potential evapotranspiration and the water balance. *Publications in Climatology*, Vol. 10 (3), 185-311.

Westin, F. C. (1976) Geography of soil test results. *Soil Sci. Soc. Am. J.*, Vol. 40, 890-895.